



Cross-country Comparison of Circular Economy Companies and the Latest Innovations in the Field

Waste Management Sector

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Information and Communication Technology – Bioeconomy Engineering Abstract
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Innovation techniques are essential to achieve sustainability in waste management and protect the environment. This study assesses different technologies in waste management and investigates their impact. Twenty case studies from different countries evaluated how they address environmental and economic effects. Power BI and Excel were used for qualitative analysis, and case studies were categorized according to country, technology, environmental impact and economic impact. Technologies were categorized into five sectors: smart waste management technologies, materials revolution: innovations in recycling, circular packaging solutions, eco-energetics: advancing waste-to-energy solutions, and circular product design for sustainability. The results show that China is the most active country among cases, and eco-energetics: advancing waste-to-energy solutions is the most popular technology. The results emphasize that these innovations create a circular economy by reducing greenhouse gas emissions, use resources more efficiently, and promote sustainable development.

Keywords Innovation methods, Circular economy, Waste management, Case study
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1 Introduction

The circular economy is a system based on making value, minimizing waste, and reducing environmental impacts. In this model, products are designed to be used for a long time, repairable, and recyclable. In addition, the circular economy helps to make value for products and services and use renewable energy. It means a linear economy that focuses on resource consumption and producing huge amounts of waste changes toward a circular economy. These days, waste management is more important because of urbanization and industrialization. The other main issue is correct waste treatment because it may damage the environment. In this regard, the role of innovations in waste management is essential.

1.1 Circular Economy

The circular economy was introduced in the late 20th century but gained massive attention in the 21st century in academic and business circles (Geissdoerfer et al., 2017, pp. 757-768.). However, it has been accepted as the primary key for environmental problems in recent years. The core principle focuses on a regenerative system where resources are continually reused and waste is minimized (MacArthur, 2013, pp. 23-44). Waste management plays a pivotal role in this system. Scientists and researchers focus on innovative approaches to reuse, recycle, and reduce waste. Companies active in waste management are at the forefront of implementing circular economy principles in both environmental sustainability and economic efficiency (Skrinjaric, 2020).

1.2 Circular Economy in Different Countries

The circular economy analysis is essential to find approaches and challenges faced in transitioning towards a sustainable development system. Comprehensive policies and objectives have been set in the European Union to accomplish sustainable development. Germany and the Netherlands have invested much money and partnerships into resource efficiency and circular business models. Reducing waste and reusing materials, strict product monitoring, and establishing recycling infrastructure are practice in these countries (van de Gronden, 2022). Customers pay for beverage containers, for instance, when they use the Pfand system, which increases recycling and decreases waste (Nauhauser & Schmidt, 2019).

In Nordic countries, its concepts are deeply accepted in the society. This achievement is because of good recycling infrastructure, strong government support, and a commitment to innovation. For example, Sweden has implemented sufficient policies for circular business models and eco-design (Swedish Environmental Protection Agency, 2021). Finland has invested in circular innovation intersections. It encourages collaboration between industry, academia, and government to gain circular economy initiatives (Finnish Ministry of Economic Affairs and Employment, 2020). One exciting method is the use of district heating systems, where heat from industrial processes or power generation is captured and reused for home heat, reducing energy consumption and emissions in Sweden (Fernqvist et al., 2023).

China and India, as emerging economies, have different challenges and opportunities to achieve an environmentally friendly system. China, the world's largest waste producer, has considered programs to promote recycling, resource recovery, and eco-friendly manufacturing. They announced regulations in whole economic sectors in 2018 (Chin & So, 2020, pp. 881-890). In this country, an electric vehicle is an interesting circular economy product, which promotes shared mobility and reduces the environmental impact of transportation (Jiang & Lian, 2024, pp. 81-101). India, as a country that experiences rapid urbanization and environmental degradation, follows different strategies for overcoming to the waste management challenges.

On the other hand, in the Middle East and Africa, circular economic techniques still need to be achieved. Most conventional linear economic model, which put short-term economic development ahead of long-term sustainability, is the significant barrier (Wang et al., 2019, pp. 741-754). Unfortunately, industry is highly dependent on resource extraction. Also, exporting is their primary goal, leading to significant waste production and environmental damage. Therefore, more funding is necessary for recycling centers and waste management infrastructures. In addition, political and legal rules must follow environmentally friendly approaches, leading to sustainable activity opportunities. These areas might find switching to a circular economic model challenging without decisive government leadership, public awareness initiatives, and motivations for sustainable corporate practices.

1.3 Waste Management

Waste management is the most essential part of the circular economy. Hopefully, some businesses aim to be 'zero-waste' leaders. It shows their goal of eliminating waste and their interest in eco-friendly concepts. They try to review their methods and emphasize efficient resource use and waste reduction. They separate recyclable materials from waste with

modern technologies, such as computer programs and intelligent devices (Korhonen et al., 2018, pp. 37-46).

Recycling is more effective in protecting valuable assets. By anaerobic digestion and burning, trash transformed into energy rather than viewing it as useless. In this way, waste becomes a valuable resource rather than at the end of the story (Bocken et al. 2016, pp. 308-320).

1.4 Project Scope and Objectives

This thesis has a research-based approach, and the criteria is to use the published articles related to innovations in waste management. The goal is to investigate innovations in the circular economy, especially in the waste management sector, and find answers to the following questions:

What are waste management approaches in different countries?

Which technologies are used by waste management companies?

Through these methods, how did waste management companies achieve sustainability?

This study is commissioned by Hyötykeräys Oy. This company focuses on sustainable waste management. They offer services to both households and businesses, and their goal is to get materials back into circulation. Circular economy and sustainable development are important values for them, and they strive to optimize the circulation of resources and minimize material waste. Its experts are trying to provide top-class waste management and circular economy services. They offer fast and expert customer service extensively in southern Finland, especially in Pirkanmaa, Satakunta, and Häme.

2 Innovation Technologies in Waste Management

Innovation is necessary to gain new opportunities in sustainability in the waste management industry. The thesis explores new developments in different parts of this area to develop

novel methods. In this chapter, the innovations in waste management categorized into five main type according to technology.

2.1 Smart Waste Management Technologies

Waste management is significant when new technologies are integrated with environmentally friendly approaches (Smith & Johnson, 2021, pp. 123-148). This revolution can affect environmentally aware societies, transportation, and efficient solutions. For example, when trash containers are equipped with sensors, waste collection routes and pickups will reduce (Anderson, 2020, pp. 287-302).

The general purpose of using artificial intelligence in waste management is to deal with waste in all its stages, including disposal at the initial point, during waste collection, and in waste processing factories. Using deep learning, machine learning, and computer vision technology, waste collection and management processes can be made more efficient and effective, and the workforce costs required to do these tasks can be reduced.

For example, one way to use artificial intelligence is to train garbage-sorting robots that can be used in landfills. Instead of requiring workers to sort the waste, these robots are trained using machine learning algorithms to identify and process waste based on the type of waste. These algorithms are taught to robots based on images of different types of waste. Using computer vision, robots can sort trash based on specific characteristics, similar to how humans compare trash. Most importantly, machines continue to learn over time and become more efficient than humans. In addition, the system can detect when the bin is full, thereby optimizing the collection schedule. Instead of sending garbage collection trucks according to a predetermined schedule, when the bins are filled to a specified level, collection routes can be optimized to only send trucks to locations where the bins are full. Such optimization increases garbage collection speed and reduces workforce and fuel costs.

Also, the consumer cannot separate some waste, so artificial intelligence technology is being developed to sort it. Smart trash cans are equipped with computer vision sensors to identify the type of trash thrown into them. For example, machine learning algorithms can train the system to identify and classify the type of discarded waste, and then the waste is thrown into the appropriate bins based on the type. This way, all the sorting is done when the waste is disposed of, and the need to sort piles at the waste processing center is eliminated.

2.2 Materials Revolution: Innovations in Recycling

Nowadays, material consumption, its production process, usage, and its end-life have an essential impact on our lives. However, traditional methods can not meet the global need as a sustainable solution. So, it is necessary to reduce material footprint by high-quality products. On the other hand, multi functional products that have been produced from simple materials could reduce the amount of waste. Sustainable materials with a variety of qualities from renewable, recycled, or recovered sources are used. For example, biodegradable products enhance circularity performance. As wastes are pseudo-renewable, they could be considered as the resources of materials and offer a more effective solution to the global issue of waste. Utilizing materials from previous sources and making them competitive is therefore the most common plan of action. Innovations in the material industry have made a revolution in the waste management sector. Green chemistry, environmentally friendly methods, and bio-based products come from biological materials such as plants, animals, enzymes, and microorganisms, such as bacteria, fungi, and yeast, are at the center of attention as one of the most resource-intensive (Brown, 2022, pp. 210-225).

The plan is to move towards a closed-loop system that considers waste as a valuable resource for producing energy, biofertilizers, and other value-added products and services. In this system, bio-based products are reused, repaired, recycled, and remanufactured. It is essential to analyze the relationship between the circular economy and bio-materials to define which cycles contribute most to a sustainable economy. For example, anaerobic digestion could be applied to a wide range of materials on both small and large scales. As it is adapted to various situations, it is a fantastic tool in the material industry (Cong & Thomsen, 2021).

2.3 Circular Packaging Solutions

Packaging is a major source of waste and has a lot of potential for recovery. Circular packaging aims to reduce the quantity of materials used and the harmful impacts of packaging on the environment over the course of its whole lifecycle as a sustainable solution (Johnson, 2021, pp. 145-162). There are other strategies accessible, such as packaging initiatives for recyclable, biodegradable, and sustainable materials. In biodegradable packaging, materials like paper, compostable materials, and plant-based polymers are broken down by microorganisms, which makes the process natural and healthy for the environment (Davis, 2020, pp. 321-335). The purpose of recyclable packaging is to be

gathered, processed, and then utilized again as an input to new goods. By lowering the demand for virgin materials, it aids in resource conservation and helps divert waste from landfills. Cardboard, glass, paper, and certain polymers are common recyclable packaging materials. The goal of circular packaging is to employ easily recyclable materials with recycled content or designed to be reused several times. Circular packaging solutions are crucial to advancing an environmentally responsible approach to packaging practices because of rising consumer consciousness and environmental concerns.

2.4 Eco-Energetics: Advancing Waste-to-Energy Solutions

Bioenergetics technologies are one of the most important parts of sustainability, especially in the future to meet the growing needs of the population (Khan et al., 2022, pp. 1708-1729). In this approach, energy is produced from waste. Nowadays the global need for energy increases and it makes concerns related to energy consumption and environmental impact. Therefore, countries try to find environmentally friendly solutions to create energy from waste as a sustainable approach. In this system, the amounts of carbon emissions decrease, and new business models are introduced (Istrate et al., 2020).

There are different environmentally friendly methods that produce biofuels, bioproduct precursors, heat, and electricity from waste. The most well-known technologies in this field are incineration, gasification, pyrolysis, and anaerobic digestion. It can generate heat or electricity or both of them (Lu et al., 2023, pp. 522-531). During the gasification process, waste including wood waste, agricultural wastes, sewage sludge, and plastic waste is partially oxidized at temperatures between 800 and 1200 degrees Celsius while a controlled amount of oxygen is present. This creates synthetic gas that can be burned again or converted into chemical feedstock (Siwal et al., 2020). Pyrolysis is the process by which waste is thermally broken down between 300 and 1300 degrees Celsius without the presence of oxygen, resulting in the liquid fuel production that can be burned again or converted into chemical feedstock (Joo et al., 2021). On the other hand, bacteria carry out anaerobic digestion, which breaks down organic waste without the presence of oxygen. Digestate and biogas are produced during digestion. Power generators can be powered by biogas. Digestate can be dewatered and utilized as a low-soil conditioner, or it can be composted as a low calorific value refuse-derived fuel (Chynoweth & Pullammanappallil, 2020, pp. 71-113).

2.5 Circular Product Design for Sustainability

Growing world population and increasing material consumption, has made the high pressure on the environment resources, so it is necessary that production be more sustainable. Imagine living in a world where the products used daily are not only highly functional but also deeply environmentally conscious. Putting sustainability at the center of the product creation process and going beyond a methods known as circular product design for sustainability actualizes this ambition (Li et al., 2020, pp. 165-179). This method rewrites the rules of product development by emphasizing recyclability, durability, and reparability through the application of circular design concepts. The old take-make-dispose approach is being replaced with a more deliberate system where items are designed to reduce their environmental impact (da Costa Fernandes, 2020). A strong and responsible future is becoming increasingly dependent on sustainability, and a critical instrument for ensuring this is circular product design.

3 Materials, Method and Limitations

This study is the literature review of case studies and it considers two main parts. Firstly, it pays attention to countries that case studies implemented. Then, it studies the innovation methods in waste management and their approaches toward sustainability. The strategy used in this research is based on case study. To answer the questions related to project, twenty case studies were chosen from scientific journals by searching the selection of library of Häme University of Applied Science using keywords such as 'waste management', 'innovation methods', 'circular economy', and 'case study' that were implemented from 2013-2024. Articles introduced in Appendix 1. The goal was to extract data including country, waste management technology that they implemented and their outcomes. Then, qualitative analysis method was chosen for evaluating. Key features were classified according to country, the circular economy approach, environmental and economic impacts. Excel and Power BI were selected for the visualization of data into word cloud, pie chart, bar chart and table to give relevant answers to the questions. After visualization, it was possible to make comparison between data to found which countries are more active in waste management; which waste treatment is more popular and what outcomes will gain. Finally, according to the founding, it is possible to suggest some approaches for Hyötykeräys Oy that achieved more to the sustainability.

On the other hand, one of the limitations of current study is the small sample size. It covers only twenty research case studies. While these case studies offer insightful analyses of waste management technologies, it is possible that they just consider the small part of the wide variety of real-world experiences and practices. So, its outcomes may not consider all issues related to waste management. Furthermore, case studies from scientific journals could miss novel methods that have not been well reported in the literatures, and could not even be applied in large scale, so this study could have bias. Therefore, future studies with a larger and more diverse sample size, including data from industry reports, government publications, and personal experience, would provide a more comprehensive understanding about innovations in waste management and their impacts on sustainability.

4 Results and Discussion

In this chapter, Firstly all twenty case studies reviewed. They were evaluated to specify the circular economy approaches, the environmental and economic impacts, country and year to give a clear view of the research's objectives. Appendix 2 summarizes the case studies. Then, their main data those are related to current study extracted. Finally, they visualized using Excel and Power BI.

4.1 Case Studies Review

According to articles, twenty case studies were selected and some data including the kind of circular economy approach, the environment and economic impacts were evaluated. Birkmaier et al. in Austria aimed to design a platform that predicts the food waste management sector by combining big data such as internal company information, the weather, and others that come from mobile phones (Birkmaier et al., 2023, pp. 708-713).

Pacheco-López et al. developed a sustainable process according to circular economy principles (Pacheco-López et al., 2023). They worked on plastic waste pyrolysis in two main stages. At the first stage, chlorine was removed from mixed plastic waste in a low-temperature reactor when lower temperatures prevented harmful emissions (dioxins and furans) into the air. Then, during the pyrolysis process in the main reactor, plastic components break down into gaseous products at high temperatures. These hot gases turn a turbine to generate electricity. Finally, via separation plates, different valuable products were purified and extracted.

Butler et al. attempted to investigate the possibilities of pectin-based films as environmentally friendly packaging materials (Butler et al., 2023). In this work, the ability of water vapor was essential because it impacted the shelf life of packed goods. Tensile strength, on the other hand, gives information on the film's durability and structural integrity by measuring how well it resists breaking when pulled or stretched. In order for products to be qualified and safe during storage and transportation, the researchers evaluated these qualities to understand how well pectin films protect packed food items from mechanical damage and moisture penetration. However, using other polymers in combination with pectin showed better quality.

Al Afif et al. converted waste from olive mills into energy using pyrolysis and hydrothermal carbonization at the University of Natural Resources and Applied Life Science in Austria (Al Afif et al., 2024). Biochar and gases are the byproducts of pyrolysis as seen in fig. During the hydrothermal carbonization process, the waste and water mixture are subjected to high temperatures and pressures, which results in the production of gases and hydrochar products. After investigation, the best procedure temperature, pressure, and time were considered in order to recover as much energy as feasible from the wasted olive oil. Biochar and hydrochar are helpful fossil fuel alternatives that can even be viewed as sustainable resources from an environmental point of view.

Chakartnarodom et al. designed high-performance fiber cement in Department of Material Engineering in Thailand (Chakartnarodom et al., 2022). The project focuses on turning traditional waste into valuable products. Through the utilization of inclusion compounds comprising hydrochloric acid, sodium thiocyanate, lithium silicate, and alkylbenzene sulfonate, she aimed to maximize the mechanical characteristics and hydration kinetics of cement samples reinforced with fibers. By means of thorough experimentation and rigorous testing, such as flammability tests and freeze-thaw resistance assessments, they demonstrated the effectiveness of their fiber-reinforced cement formulations in achieving industrial standards with the least possible impact on the environment. They replaced sand with recycled fiber cement to reduce greenhouse gas emissions and resource consumption.

In addition, in China, Wang et al. investigated the environmental and economic impact of integrated municipal solid waste management treatment centers using a combined life cycle assessment and life cycle costing methodology (Wang et al., 2020). It was an environmental and economic quantitative investigation of waste treatment, including waste separation, brick making and plastic recycling, using life cycle assessment and life cycle costing methodologies. Wang & Nakakubo evaluated energy balance and greenhouse gas

emissions during the landfill and incineration methods by comparing the waste semi-aerobic and anaerobic landfills and incineration methods (Wang & Nakakubo, 2020).

Wen et al. analyzed the carbon metabolism in waste treatment systems including landfilling, composting, incineration, and anaerobic digestion. They evaluated the reduction of environmental pollution caused by different carbon compounds like CO₂, CH₄, CO, COVs and other organic materials during waste treatment. Life cycle impact analysis and sensitivity analysis methods are used to assess the environmental impacts. According to the results, under optimized condition, the most pollution reduction could occur, so it is important to apply optimized waste treatment technology on the waste (Wen et al., 2019, pp. 512-523).

Shan et al. determined the environmental impact of residents participating in waste management treatment by complying with micro-survey data using a statistical model. According to the results, years of residents' education, their household status, and income have a direct effect on residents' participation in waste management (Shan et al., 2021, pp. 1170-1186).

Zhu et al. developed an evaluation method for waste treatment capacity based on prediction using artificial intelligence. The procedure started by creating a prediction model and using the artificial neuron network according to the statistical data of Jiangsu Province of China from 1990 to 2020. Then, the finalized model that had the input variables. The model structure that includes four hidden layers and sixteen neurons in each hidden layer performed the best (Zhu et al., 2024, pp. 9948-9963).

Chen et al. defined a solid agricultural and industrial waste source as the direct production site of solid waste. They proposed controlling pollution directly at its source instead of focusing on removing pollution from water or soil. In their study, three methods were employed, including energy-saving, emission reduction, and resource utilization, along with transportation, storage, and treatment. Additionally, they suggested using piggeries with waste-absorbing land to achieve solid waste pollution control at its source (Chen et al., 2020).

Minoglou and Komilis in Greece developed a method including incineration, composting, anaerobic digestion, and landfilling after waste separation to optimized the total cost of municipal solid waste and minimize the CO₂ emissions generated by the whole system (Minoglou & Komilis, 2013, pp. 46-57).

In India, Tyagi et al. conducted an analysis of a one-hundred-ton-per-day mechanical biological treatment plant. The study focused on waste valorization, material and energy recovery, organic extraction, thermophilic anaerobic digestion, composting, effluent treatment plant, and biogas production. The results encouraged Tyagi's team to perform this project for a long time in India, and they gained 12% recyclable products, 33% refused derived fuel, 0.435 MWh/d electricity, 5% compost, and 70 m³/d water recovered. In addition, biogas and methane yields were produced as they were supposed to be from the life cycle assessment study (Tyagi et al., 2021). Ansari et al. developed a comprehensive analysis of waste management systems. To achieve sustainability, they used smart technologies to evaluate numerous green strategies in different countries. According to the results, they emphasized the urgent need for creative and sustainable waste treatment solutions in the face of the world's growing population. Solutions should be suitable for the specific needs of any place and focus on sustainability that holds the local market's roles in sustainable waste management (Ansari et al., 2024, pp. 29-38).

A comparative approach for the resilience engineering evaluation in the municipal solid waste treatment industry was developed by Rubio-Romero et al. in Spain and Italy. The goal was to facilitate a health and safety management decision simulation based on their impact on resilience engineering in municipal solid waste treatment and collection companies. The data was collected via survey filled out by industrial workers. The results emphasized the priority of learning culture, improving top-level commitment, and increasing awareness related to waste treatment and its outcomes (Rubio-Romero et al., 2018, pp. 613-622).

Paladino and Massabò in Italy made a relationship between health issues and waste treatment technology. In fact, they evaluated the hazard index and cancer index during two different waste treatment approaches: traditional disposal methods and alternative waste-to-energy methods. According to the results, the gasification of total dry and wet waste should be eliminated because of the unacceptable production of dioxins and NO_x gases. On the other hand, gasification of the dry waste followed by anaerobic digestion of the wet fraction, along with biogas combustion and disposal of sludge and bottom ash/slag in the old landfill, has been selected as the best waste treatment method with the least amount of health risk (Paladino & Massabò, 2017, pp. 344-354).

Costa et al. developed a public awareness related to waste management in Portugal. They gathered information from online questionnaires and finally found that most people in Portugal were not aware of waste management, but they were interested in knowing more and more positively. According to the results, age and sex influence people's decisions

regarding waste, and there is a significant relationship between recycling and considering economic matters (Costa et al., 2022).

The construction industry produces the most landfilled waste in Hong Kong, but concerns are related to limited landfill capacity. Kang et al. designed a conceptual framework that integrated advanced smart technologies like the Internet of Things (IoT) for buildings to maximize waste reuse and recycling through smart building information modeling. It provided sufficient data collection and analysis, showed optimal disposal route selection, offered technical and decision-making support to engineers and planners, and showed fantastic benefits in both environmental and economic aspects (Kang et al., 2022, pp. 69-73).

As Indonesia has challenges related to waste collection, transportation, processing, and landfill; Fatimah et al, used industry 4.0 technologies. It was a multi-dimensional approach, to assess the maturity level of waste management and design new strategies to minimize problems. It enhances waste treatment efficiency, reduces costs, create jobs, and sustainable waste treatments (Fatimah et al., 2020).

Roy et al. designed a waste management approach integrating IoT technology with smart bins to increase collection efficiency in South Korea. It was a central monitoring system and vehicle routing algorithm that led to proper collection time, minimized overflowing bins, and improved resource allocation (Roy et al., 2022).

4.2 Analysis

This part involved a thorough evaluation of case studies to address the research questions. Each case study was reviewed according to key features, such as country, waste management approaches, environmental and economic impacts. Data collected from the case studies were visualized using Excel and Power BI, facilitating the identification of trends, patterns, and insights. Through this analysis, valuable insights were gained into the effectiveness of different waste management technologies and strategies across various countries.

4.2.1 Waste Management in Different Countries

As shown in figure 1, the region where case studies were implemented was analyzed by Power BI. In this figure, the circle's diameter indicate the number of activities.



Figure 1. The region where case studies were implemented.

China is prior and India is the next active country according to figure 2, among the case studies, China, with 33%, is the most active country, especially in the eco-energetics: advancing waste-to-energy solutions sector. Figure 3 illustrates China's activity in different waste management technologies. The eco-energetics: advancing waste-to-energy solutions sector is the most interesting technique with 43% of waste management activities, and circular packaging solutions with 29% is the next popular activity. India is closely behind by high interest in smart waste management technologies like IoT. It is an interesting technology for Indonesia, too. However, other countries such as South Korea, Greece, Spain, Italy, Austria, Ireland, Portugal, Montenegro, and Thailand are active in waste management with 5% participation.

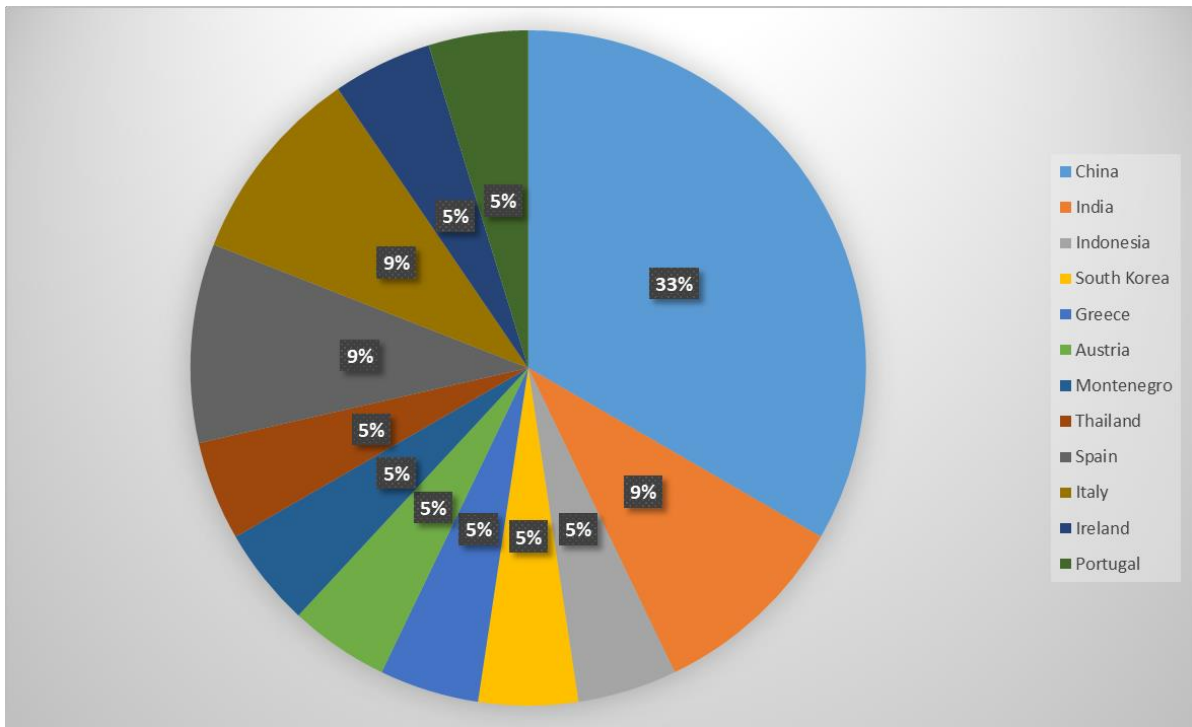


Figure 2. The frequency by country's activity in waste management.

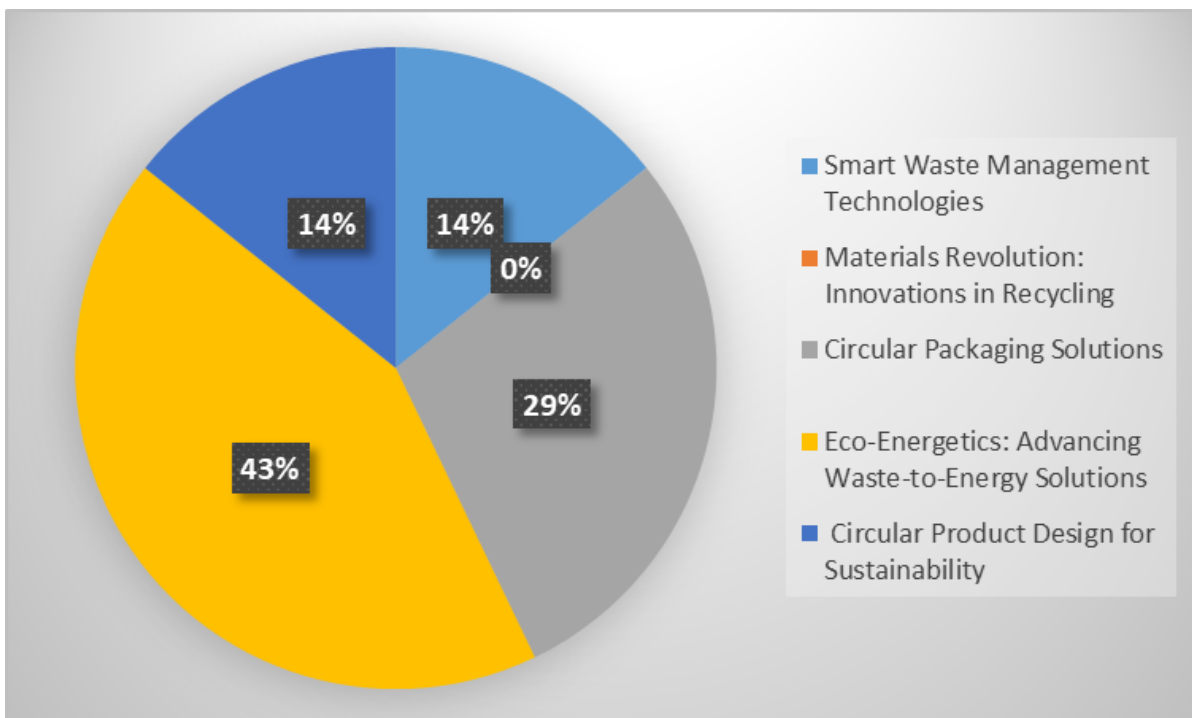


Figure 3. The frequency by China's waste management technology.

4.2.2 Innovations Technologies Analysis

The technologies used in case studies evaluated to find which technology is the most popular and most used by companies. As shown in figure 4, different technologies are applied in the case studies. eco-energetics: advancing waste-to-energy solutions was the most interesting technology with 37%. 32% of case studies were designed according to the smart waste management technologies. Circular packaging solutions and circular product design for sustainability technologies are at the next level at 16% and 10%, respectively. Material revolution: innovations in recycling technology, which makes up 5% of the case studies, completes the technical landscape.

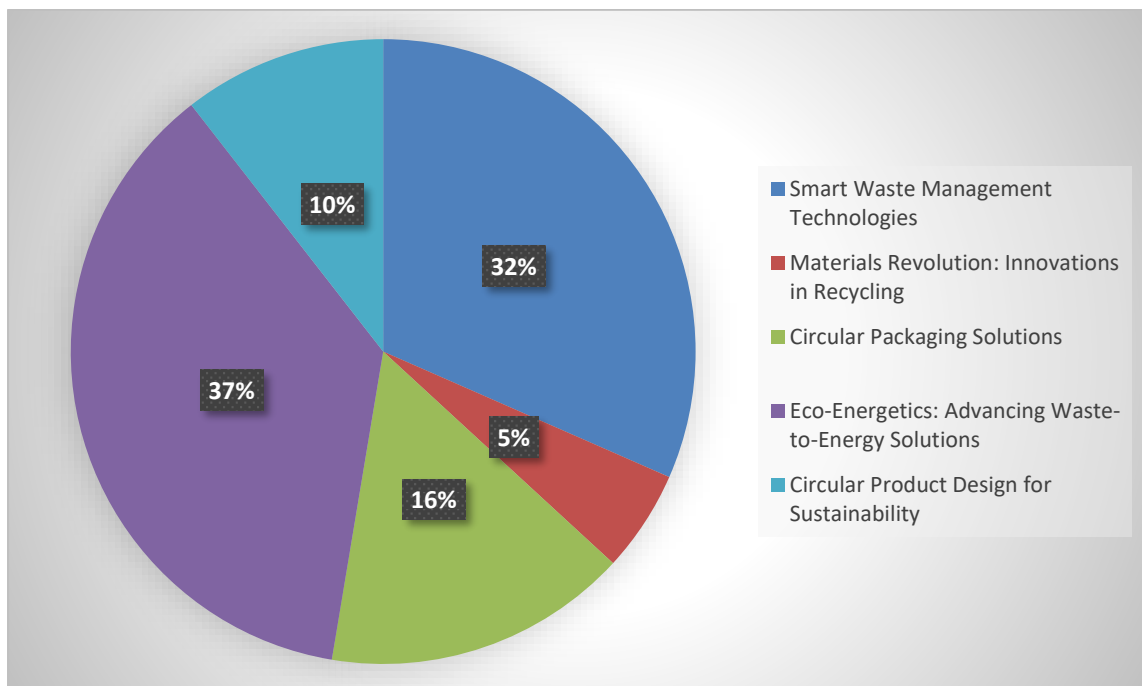


Figure 4. Frequency of waste management technology among case studies.

Figure 5 illustrates the number of waste management technologies utilized in any country. Eco-energetics: advancing waste-to-energy solutions is particularly popular in countries like China, Greece, Italy, and Montenegro. Reduction in greenhouse gas emissions and recovering energy from waste are the two main goals of this method, which is good for the economy and the environment. The smart waste management technologies is popular in Portugal, China, India, and South Korea. However, China demonstrated activities in circular packaging solutions and circular product design for sustainability technologies, too.

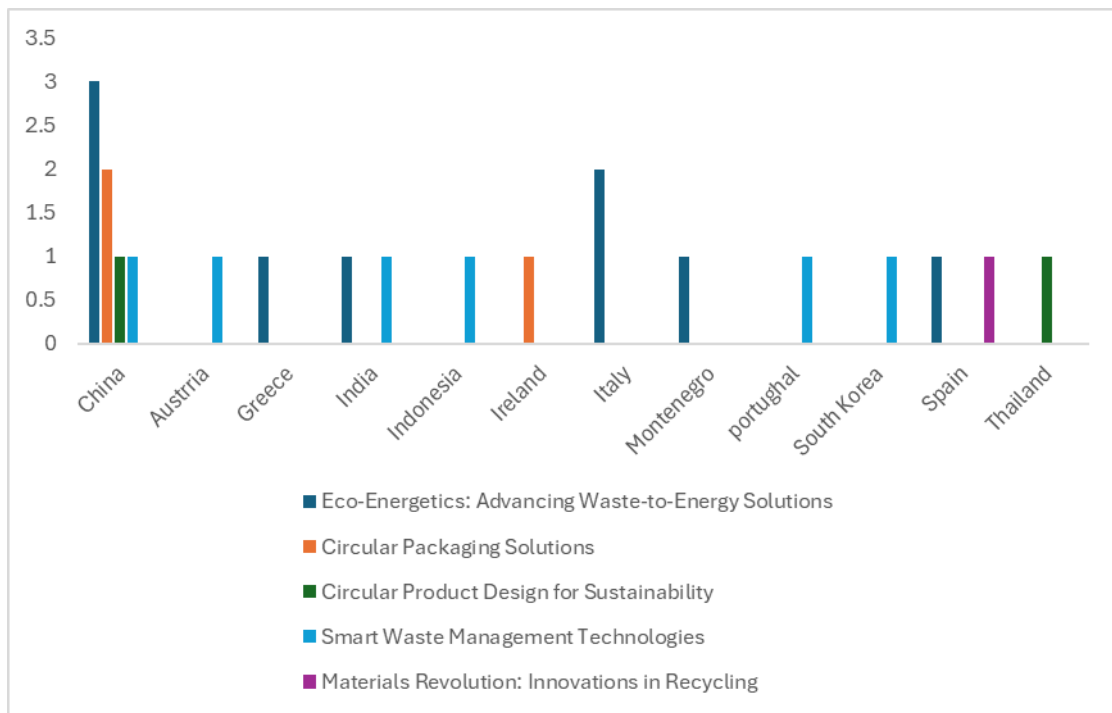


Figure 5. The number of waste management technologies utilized by country.

All countries try to reduce greenhouse gas emissions and decrease resource utilization. In addition, energy recovery is a challenge for the majority of them. China and India encountered rapid industrialization and urbanization, so a huge amount of waste produced every day. China efforts to reduce greenhouse gas emissions and decrease resource utilization. In addition, its focus on the eco-energetics sector reflects its proactive approach to addressing environmental challenges. On the other hand, India tries to adapt to smart technologies and innovative solutions for efficient waste management to achieve urban development.

4.2.3 Environmental Impacts Analysis

Environmental impacts analyzed to understand how these waste management technologies were in a sustainable approach. Power BI used to create word cloud that the size of a word depends of the frequency the environmental impacts among consequences represented in the data. The word cloud in figure 6 shows the environmental impacts of waste management technologies used in case studies. They are energy recovery, reduced resource utilization, reduced greenhouse gas emissions, renewable energy, decreased landfill implications,

increased public awareness, advanced forecasting, chemical recycling, compostable packaging, food waste reduction, improved waste collection efficiency, IoT integration, and renewable materials.

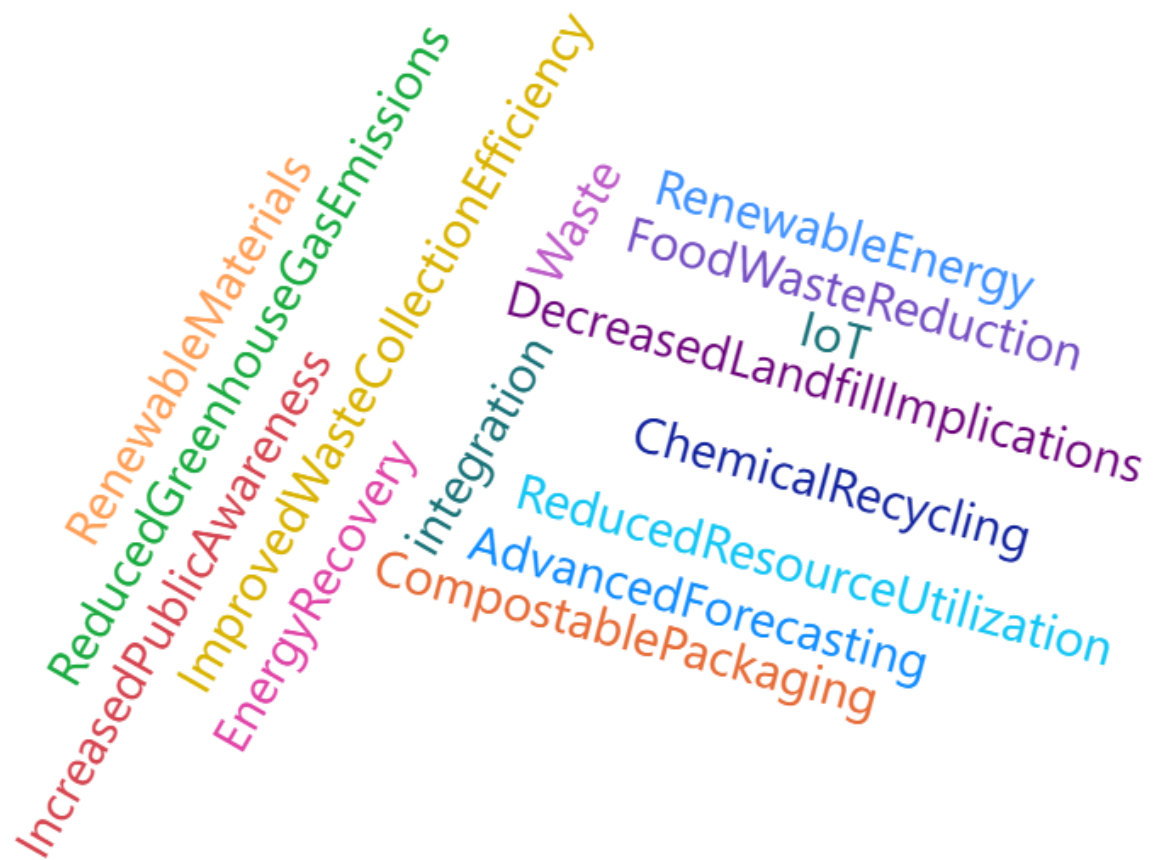


Figure 6. The environmental impacts of waste management technologies used in case studies.

Then, environmental impact of any waste management technology evaluated. Table 1 shows the environmental benefits related to any waste treatment approach. According to the table, similar impacts were achieved by different technologies.

Table 1. The environmental benefits of any technology.

Technology	Environmental Impact
Eco-Energetics: Advancing Waste-to-Energy Solutions	Energy Recovery, Reduced Resource Utilization, Reduced Greenhouse Gas Emissions, Decreased Landfill Implications, Renewable Energy
Smart Waste Management Technologies	Improved Waste Collection Efficiency, Increased Public Awareness, IoT integration, Reduced resource utilization, Decreased Landfill Implications, Advanced forecasting, Food Waste Reduction
Circular Packaging Solutions	Compostable Packaging, Reduced Resource Utilization, Energy Recovery, Renewable Materials
Circular Product Design for Sustainability	Renewable Materials, Reduced Resource Utilization, Reduced Greenhouse Gas Emissions, Renewable Energy
Materials Revolution: Innovations in Recycling	Chemical Recycling, Reduced Resource Utilization, Renewable energy

The pie chart in figure 7 illustrates the percentage of any impact. energy recovery and reduced resource utilization are the most common environmental outcomes, each with 22% of total impacts. reduced greenhouse gas emissions and renewable energy are in the second line, each with 14%. Then, it follows with decreased landfill implications and increased public awareness, with 7% and 5%, respectively. Other impacts are less common.

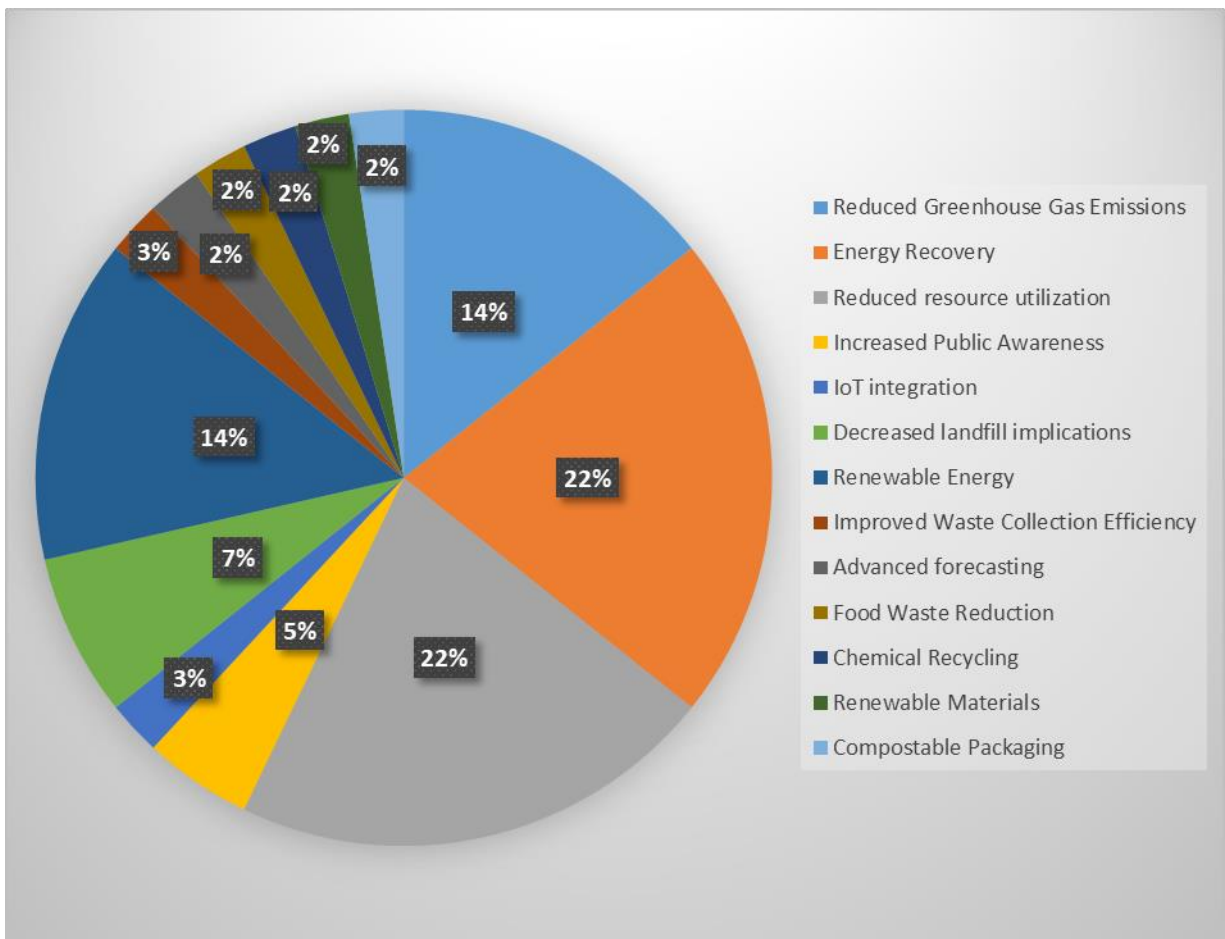


Figure 7. The frequency of any environmental impact.

As the point of sustainability, companies utilized different waste management technologies that led to various environmental impacts. With energy recovery and reduced resource utilization, companies could minimize waste while making value from them and reducing reliance on resources. However, companies considered all environmental impacts as tries to overcome climate change, minimize environmental harm and increase social responsibility. In addition, moving in a reliable way to optimize their operations for sustainable efficiency and effectiveness in waste management.

4.2.4 Economic Impacts Analysis

Power BI performed the economic effect analysis based on case studies. The word cloud in figure 8 depicts several economic benefits, such as decreased energy demand, reduction of oil dependence, cost reduction, technological adaptation, job creation, financial return, trading market enhancement, higher income, and more willingness to pay.



Figure 8. The economic impacts of waste management technologies used in case studies.

The frequency of each category of economic impact is shown in figure 9 with cost reduction accounting for 31% of all outcomes across case studies, it was the most prevalent economic consequence. The frequency of each other's economic effects is between 7% to 8%.

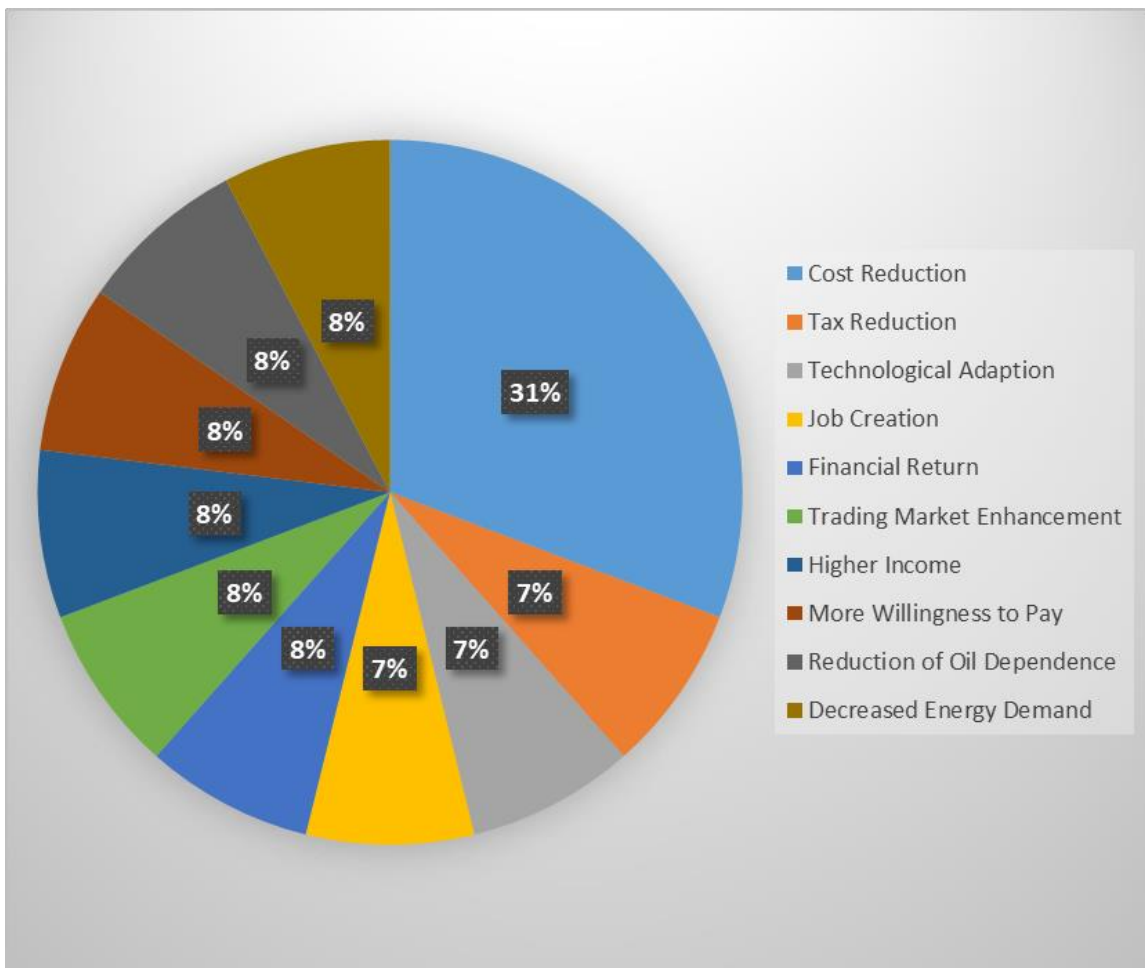


Figure 9. The frequency of any economic impact.

From an economic point of view, the technologies applied in case studies enabled waste management companies to move towards a more sustainable future. According to the gained outcomes, companies could optimize their operations for efficiency and competitiveness. In addition, with a decrease in oil dependency, they could save money and have a green and sustainable transit system.

4.3 Discussion

According to cross-country evaluation, different strategies are applied to waste. China demonstrated more efforts in waste management especially in the waste-to-energy technologies. It shows its need for a big population and industry. The next active country was India with more interest in smart techniques in waste treatment. The other countries showed their interest in innovations in waste management such as South Korea, Greece, and Italy with lower levels.

Waste management technology analysis shows a variety of innovations. Eco-energetics solution was the most popular technology, followed by smart waste management technology, circular packaging solutions, and circular product design for sustainability. Various methods such as energy recovery, machine learning algorithms, and innovative packaging materials were involved in these technologies and helped companies achieve sustainability.

Companies achieved sustainability through adopting new approaches including waste-to-energy solutions and smart waste management technologies for data analysis, optimizing route and time collection, and faster waste processing. Using material modification, circular packaging solutions, and sustainable product design, companies reduced waste production, decreased greenhouse gas emissions, increased recycling and resource efficiency, and energy recovery as well as cost reductions.

5 Conclusions

The study aimed to compare innovation technologies applied to waste management in different countries and show how they achieved sustainability. Twenty cases were studied, and results were analyzed qualitatively using Excel and Power BI. The findings support sustainability and moving in a circular economy approach. They focus on eco-friendly energy solutions and smart waste management systems. Among case studies, China is the most activated country and focuses on eco-friendly energy solutions that lead to decrease in greenhouse gas emissions and reduction in resource consumption.

Meanwhile, countries such as India and South Korea increasingly adopt smart waste management technologies, such as integrating IoT. According to the results, it is clear that companies achieved environmentally friendly approaches when they benefited from energy recovering and using resources more efficiently, reducing greenhouse gas emissions, decreasing landfills, forecast facilities, and renewable materials. In addition from economic point of view, these methods led to cost savings and reduced dependency on fossil fuels. So, investing in these technologies is crucial for creating a more sustainable future while companies gain economic benefits. Furthermore, studies could encourage companies to participate more in eco-friendly waste treatment methods and advantages from economic growth.

Based on insights gained from this study, it is suggested that Hyötykeräys Oy could benefit from artificial intelligence in waste management to deal with waste in all its stages, including

disposal at the initial point, during waste collection, and in waste processing separation. Integrate smart technologies such as IoT-enabled sensors and smart bins and enhance waste management efficiency by providing real-time data on waste levels and optimizing collection routes. Optimized route and transit solutions can further facilitate operations, reduce fuel consumption, and minimize environmental impact. However, while artificial intelligence can certainly enhance waste management practices, it is essential to consider its implementation within the context of Finland's waste management regulations and infrastructure. Some aspects, such as artificial intelligence-powered sorting robots, may require careful consideration due to existing waste sorting systems in Finland. The other possibility is using garbage-sorting robots that can be used in landfills. Instead of requiring workers to sort the waste, these robots are trained using machine learning algorithms to identify and process waste based on the type of waste. However, it might not be as necessary in Finland due to the country's well-established waste sorting infrastructure, but there could still be potential for their use in specific scenarios or to complement existing systems. Using smart trash is the other option that the collection bins are equipped with computer vision sensors to identify the type of trash thrown into them. For example, machine learning algorithms can train the system to identify and classify the type of discarded waste, and then the waste is thrown into the appropriate bins based on the type, and separation occurs in the first step. In addition, the company can design a user-friendly mobile application which people trace the waste transit and treatment process, outcomes, and environmental benefits such as carbon footprint reductions, and cost savings. It increases public awareness and will increase willingness to waste separation and collection.

For future studies, these suggestions could be considered:

Analyzing more case studies enhances accuracy.

Comparing two or more experiments that provide deeper insights into waste management approaches in different conditions.

Calculating life cycle analysis for waste transit offers valuable insights into the environmental impacts of waste management practices at different stages.

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Appendix 1. Case studies.

Case Study	Title	Authors	Year	Journal	Volume
1	Environmental and Economic Performance of an Integrated Municipal Solid Waste Treatment: A Chinese Case Study	Wang Zhiguo, Lv Jingxiang, Gu Fu, Yang Jie, Guo Jianfeng	2020	The Science of the total environment	709
2	Catalyzing Paradigm Shifts in Global Waste Management: A case study of Saharanpur Smart City	Ansari Abdullah, Dutt Dharm, Kumar Vivek	2024	Waste Management Bulletin	2
3	Industry 4.0 Based Sustainable Circular Economy Approach for Smart Waste Management System to Achieve Sustainable Development Goals: A Case Study of Indonesia	Fatimah Yun Arifatul, Govindan Kannan, Murniningsih Rochiyati, Setiawan Agus	2020	Journal of cleaner production	269
4	Comparative Assessment of Waste Disposal Systems and Technologies with Regard to Greenhouse Gas Emissions: A Case Study of Municipal Solid Waste Treatment Options in China	Wang Kehua, Nakakubo Toyohiko	2020	Journal of cleaner production	260

5	Building demolition waste management through smart BIM: A case study in Hong Kong	Kang Kai, Besklubova Svetlana, Dai Yaqi, Zhong Ray Y.	2022	Waste management	143
6	Environmental Impact of Carbon Cross-Media Metabolism in Waste Management: A Case Study of Municipal Solid Waste Treatment System in China	Wen Zongguo, Chen Chen, Ai Ning, Bai Weinan, Zhang Wenting, Wang Yihan	2019	The Science of the total environment	674
7	The Impact of Environmental Benefits and Institutional Trust on Resident's Willingness to Participate in Municipal Solid Waste Treatment, A Case Study in Beijing, China	Shan Shao-nan, Duan Xia, Zhang Ting-ting, Zhang Yi, Wang He	2021	International journal of low carbon technologies	16
8	IoT - Based Smart Bin Allocation and Vehicle Routing in Solid Waste Management: A Case Study in South Korea	Roy Arindam, Manna Apurba, Kim Jungmin, Moon Ilkyeong	2022	Computers & industrial engineering	171
9	Spatial-Temporal Redundancy Evaluation of The Municipal Solid Waste Incineration Treatment Capacity: The Case Study of China	Zhu Lei, Tian Zhuoyu, Du Jing	2024	Environmental science and pollution research international	31

10	Optimizing the Treatment and Disposal of Municipal Solid Wastes Using Mathematical Programming – A Case Study in a Greek Region	Minoglou Minas, Komilis Dimitrios	2013	Resources, conservation and recycling	80
11	Mechanical – Biological Treatment of Municipal Solid Waste: Case Study of 100 TPD Goa Plant, India	Tyagi Vinay Kumar, Kapoor Aparna, Arora Pratham, Banu J. Rajesh, Das Sukanya, Pipesh Shubham, Kazmi A.A.	2021	Journal of environmental management	292
12	Spatial Classification and Environmental Treatment Protocols of Solid Waste Sources, A Case Study of Shengzhou, China	Chen Yufan, Xu Yong, Wang Kaiyong	2020	Sustainability	12
13	Comparative study of Resilience Engineering in Solid Waste Treatment Plants: A Case Study in Two European Cities	Rubio-Romero Juan Carlos, Molinillo Sebastian, López-Arquillos Antonio, Arjona-Jiménez Rafael, De La Varga-Salto José María	2018	Work (Reading, Mass.)	60
14	Health Risk Assessment as an Approach to Manage an Old Landfill and to Propose Integrated	Paladino O., Massabò M.	2017	Waste management (Elmsford)	68

	solid Waste Treatment, A Case Study in Italy				
15	Preventing Waste in Food Supply Network – A Platform Architecture for AI – Driven Forecasting Based on Heterogeneous Big Data	Birkmaier Alexandra, Imeri Adhurim, Riestert Martin, Reiner Gerald	2023	Procedia CIRP	120
16	Integrated Synthesis, Modeling, and Assessment (iSMA) of Waste-to-Resource Alternatives Towards a Circular Economy: The Case of the Chemical Recycling of Plastic Waste Management	Pacheco-López Adrián, Gómez-Reyes Edward, Graells Moisés, Espuña Antonio, Somoza-Tornos Ana	2023	Computers & chemical engineering	175
17	Pectin as a Biopolymer Source for Packaging Films Using a Circular economy Approach: Origins, Extraction, Structure and Films Properties	Butler Ian P., Banta Russell A., Tyuftin Andrey A., Holmes Justin, Pathania Shivani, Kerry Joe	2023	Food packaging and shelf life	40
18	Evaluation of Biochar and Hydrocar Energy Potential Drived from Olive Mills Waste: The Case of Montenegro	Al Afif Rafat, Kapidžić Minea, Pfeifer Christoph	2024	Energy (Oxford)	290
19	Development of High – Performance Fiber Cement: A Case Study in the Integration of	Parinya Chakartnarodom, Sarunya Wanpen, Wichit Prakaypan, Edward A. Laitila,	2022	Sustainability	14

	Circular Economy in Product Design	Nuntaporn Kongkajun			
20	A Social Receptiveness Analysis on Smart Waste Management – A Case Study for Portugal	Costa Madalena, Madureira Raquel Castro, Dias-Ferreira Celia	2022	Sustainable chemistry and pharmacy	28

Appendix 2. Case studies' summary.

Case Study	Technology	Environmental Impacts	Economic Impacts	Country
1	Eco-Energetics: Advancing Waste-to-Energy Solutions	Reduce Greenhouse Emissions, Energy Recovery, Reduce resource utilization	Reduce Equipment Costs and Taxes	China
2	Smart Waste Management Technologies	Increased Public Awareness	Technological Adaption	India
3	Smart Waste Management Technologies	Decrease landfill implications, IoT Integration, Reduce resource utilization	Cost Reduction, Job Creation	Indonesia
4	Eco-Energetics: Advancing Waste-to-Energy Solutions	Reduce Greenhouse Emissions, Energy Recovery, Decrease landfill implications	Not Specified	China
5	Smart Waste Management Technologies	Decrease landfill implications, Reduce Resource Utilization	Cost Reduction, Financial Return, Trading Market Enhancement	China
6	Eco-Energetics: Advancing Waste-to-Energy Solutions	Reduce Greenhouse Emissions, Energy Recovery, Reduce Resource Utilization	Not Specified	China

7	Circular Product Design for Sustainability	Renewable Energy, Reduce Resource Utilization	Higher Income, More Willingness to Pay	China
8	Smart Waste Management Technologies	Improved Waste Collection Efficiency	Not Specified	South Korea
9	Circular Packaging Solutions	Reduce Resource Utilization, Energy Recovery	Reduce Disposal Cost	China
10	Eco-Energetics: Advancing Waste-to-Energy Solutions	Reduce Greenhouse Gas Emissions, Energy Recovery, Renewable Energy	Not Specified	Greece
11	Eco-Energetics: Advancing Waste-to-Energy Solutions	Energy Recovery, Renewable Energy,	Not Specified	India
12	Circular Packaging Solutions	Reduce Resource Utilization	Not Specified	China
13	Eco-Energetics: Advancing Waste-to-Energy Solutions	Energy Recovery, Renewable Energy	Not Specified	Spain and Italy
14	Eco-Energetics: Advancing Waste-to-Energy Solutions	Reduce Greenhouse Gas Emissions,	Not Specified	Italy

		Energy Recovery, Renewable energy		
15	Smart Waste Management Technologies	Advanced forecasting, Food Waste Reduction	Not Specified	Austria
16	Materials Revolution: Innovations in Recycling	Reduce Resource Utilization, Chemical Recycling, Renewable energy	Not Specified	Spain
17	Circular Packaging Solutions	Renewable Materials, Compostable Packaging,	Reduction of Oil Dependence	Ireland
18	Eco-Energetics: Advancing Waste-to-Energy Solutions	Energy Recovery	Decrease Energy Demand	Montenegro
19	Circular Product Design for Sustainability	Reduce Greenhouse Gas Emissions, Reduce Resource Utilization	Not Specified	Thailand
20	Smart Waste Management Technologies	Increase Public Awareness	Not Specified	Portugal